

Re-discovery of the top quark at the LHC and first measurements

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Summary. — This paper describes the top quark physics measurements that can be performed with the first LHC data in the ATLAS and CMS experiments.

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1. – Top quark production at the LHC

The Large Hadron Collider (LHC) is the new CERN proton-proton collider that will start taking data in the course of 2008. Initially the collisions will take place at $\sqrt{s} = 10$ TeV, moving on to the planned $\sqrt{s} = 14$ TeV in early 2009.

Top quarks at the LHC are produced mainly in $t\bar{t}$ pairs via gluon fusion or $q\bar{q}$ scattering. The gluon-fusion mechanism accounts for about 90% of the cross-section and the onset of this subprocess at high energy is responsible for the much larger cross-section at the LHC compared to the Tevatron at Fermilab. The total pair-production cross-section is estimated [1] to be $\sigma(t\bar{t}) = (833^{+52}_{-39})$ pb. Single top production occurs via electroweak interactions, with a total cross-section of about 300 pb.

Because $|V_{tb}| \simeq 1$, the top quark decays almost always as $t \rightarrow Wb$. $t\bar{t}$ events can be then classified depending on how the W decays as: *hadronic* if both W 's decay hadronically (branching ratio $\text{BR} \simeq (2/3)^2 \simeq 44\%$), *semi-leptonic* if one W decays leptonically and one hadronically ($\text{BR} \simeq 2 \times 1/9 \times 2/3 \simeq 15\%$ for each lepton type e , μ or τ) or *di-leptonic* if both W 's decay leptonically ($\text{BR} \simeq (1/3)^2 \simeq 11.1\%$).

$t\bar{t}$ events can be used to investigate many relevant observables and properties of top quarks: production cross-section, top-quark mass, charge, polarization, rare decays, such as the ones involving flavour changing neutral currents (FCNC). The top quark is the heaviest and less studied quark: the study of its properties may open a window to new physics. $t\bar{t}$ events are also going to be important as a ‘validation tool’ of many physics

variables: in fact, $t\bar{t}$ events contain leptons, jets, b -jets and missing transverse energy. They can therefore be used to study the b -tagging performance and calibrate the jet energy scale. The quick observation of top-quark pair events will give the needed credibility to possible signals of new physics. Top events also constitute an important background for many searches beyond the Standard Model: as a first step, the distributions of all important kinematic variables of these events must be well understood.

Most of the top properties studies are performed using the semi-leptonic or di-leptonic channels, since the presence of isolated leptons and missing energy ensure a higher purity than the all-hadronic channel.

In this paper we describe the $t\bar{t}$ event topology, selection and possible measurements, with particular emphasis on the early data. The LHC luminosity will gradually increase in the first months; here we review the experiments potential in the top physics sector for a typical integrated luminosity between 100 pb^{-1} and 1 fb^{-1} .

A typical selection for 100 pb^{-1} has to take into account that the detector may not be perfectly calibrated and aligned. As a consequence, physics analysis tools like b -tagging or missing energy calculation will not be yet fully commissioned. Trigger selections and offline selection cuts must then rely on simple and robust criteria.

2. – Event selection

2.1. Semi-leptonic events. – Semi-leptonic events with one electron or muon in the final state are characterized by one isolated lepton, some missing transverse energy, two heavy flavour jets and two light jets. The main backgrounds are single W boson production with associated jets, including the heavy-flavour channel ($Wb\bar{b}$ +jets), and QCD events with heavy flavour jets which produce leptons from B decays or fake leptons.

In the early data-taking period, the most reliable triggers to study these events will likely be the single-lepton triggers, which typically have a threshold at $p_T \simeq 20 \text{ GeV}$. Additional cuts will then be performed offline to improve the lepton identification and the isolation. At least four jets are required in the event within the tracker acceptance. b -tagging can be applied to these if a particular analysis requires it. Often a loose cut on the missing E_T is applied, as well as additional kinematic cuts on the reconstructed W and top masses, or on the scalar sum of the transverse energies of leptons and jets. A typical efficiency in this channel is around 5% and the signal over background ratio $S/B \simeq 3$.

2.2. Di-leptonic events. – Di-leptonic events with electrons or muons in the final state are characterized by two isolated leptons, missing transverse energy and two heavy flavour jets. The main backgrounds in this channel are single $Z \rightarrow l^+l^-$ or $W \rightarrow l\nu$ production with associated jets, including heavy-flavoured jets. In the W boson events the second lepton can arise from the decay of heavy flavour jets or from a fake. Boson pair production is also an important background.

The presence of two isolated leptons allows one to select these events with high purity, especially the $e-\mu$ channel. These events often fire the single- and double-lepton triggers, following which additional cuts can be applied offline to improve the lepton identification and isolation. Two jets are required in the event within the tracker acceptance in order to perform the b -tagging, if needed. A missing- E_T cut and cuts on the reconstructed dilepton mass further suppress the QCD and Z backgrounds. A typical efficiency in this channel is around 3-4%, with a signal over background ratio $S/B \simeq 5 - 10$.

2.3. Startup scenario. – A CMS study [2, 3] has shown that already with 10 pb^{-1} it is possible to select some top-pair events and reconstruct a mass peak, as shown in Figure 1. This Monte Carlo study simulates mis-calibrated calorimeters and a mis-aligned tracker in realistic startup conditions. Relaxed cuts are applied in the event selection and redundancy in the reconstruction process is used. For example, jets are reconstructed both with calorimeters and by using tracks, and lepton-based b -tagging is employed, instead of methods based on vertex reconstruction.

3. – Analysis for \mathcal{L} between 100 pb^{-1} and 1 fb^{-1}

Both CMS and ATLAS have performed detailed Monte Carlo studies of the top physics reach with an integrated luminosity between 100 pb^{-1} and 1 fb^{-1} [4, 5]. A typical selection for 100 pb^{-1} has to take into account reduced detector calibration and alignment, and the possibility to evaluate efficiencies directly from the data.

In the CMS study [4] the calorimeter calibration and tracker alignment are mis-calibrated at a level that is expected to be reachable with 100 pb^{-1} integrated luminosity. Jets are reconstructed using the iterative cone algorithm; the missing transverse energy is calculated using calorimetric towers and taking into account the muon momentum. Both options to use or not the b -tagging are considered. In the first case, b -jets are identified using the track-counting algorithm and a loose b -tagging is generally employed. This simple algorithm considers the transverse impact parameter of the N -th track in a jet, where the tracks are sorted by impact parameter. In the di-leptonic events with taus ($e\tau$ and $\mu\tau$), the τ -jet tagging algorithm is used to select a narrow, isolated calorimetric jet, well matched with one or three tracks and possibly with some indication of large impact parameter. Techniques to evaluate the efficiency and misidentification rate for the b -tagging and lepton-selection directly from the data have been studied.

In ATLAS, the cross-section is determined both in the semi-leptonic and dilepton channel. For the semi-leptonic channel the measurement is performed with and without relying on b -tagging. A strategy is studied to evaluate the W +jets background normalization using the inclusive W , Z and Z +jets cross-sections via the following relation: $\sigma(W_{\text{incl}})/\sigma(W + nj) = \sigma(Z_{\text{incl}})/\sigma(Z + nj)$, which is valid to a few percent level as suggested by [6].

A crucial point in these analyses is the control of the QCD background, characterized by a very large cross-section and small efficiency. Thus, extremely large Monte Carlo samples would be needed to correctly estimate the contamination by these processes. To calculate the efficiency, two techniques were used by the CDF and D0 experiments at the Tevatron: the cut factorization and the ‘matrix’ method. The cut-factorization technique consists in finding two sets of uncorrelated cuts, measuring the two efficiencies separately on Monte Carlo events and assuming that the total efficiency is the product of the two. The matrix method estimates the QCD background directly from the data by extracting the QCD efficiency in a signal-free control region, by loosening one of the analysis cuts.

4. – Top Physics Reach at Start-up

Both ATLAS and CMS are putting great effort into studies with very low integrated luminosity. The first measurement is the rediscovery of the top quark: event selection in the di-lepton and semi-leptonic channels and mass peak reconstruction. This is within reach already with about 10 pb^{-1} .

With about 100 pb^{-1} , the $t\bar{t}$ cross-section can be measured with an error of the order of 15%, and a first mass measurement can be given with a few hundred pb^{-1} . However, a precise mass measurement (below 1 GeV precision) requires detailed understanding of many systematic effects, due to both the detector and the techniques of analysis: calibrations, energy scales, missing-energy evaluation, possible biases in kinematic reconstructions, etc.

4.1. $t\bar{t}$ Invariant Mass Spectrum. – Starting from $\mathcal{L} = 1 \text{ fb}^{-1}$ ATLAS [7] and CMS will give a measurement of the $t\bar{t}$ invariant-mass spectrum. This spectrum will be sensitive to $t\bar{t}$ resonances and other new physics effects. Figure 2 shows the expected ATLAS reach for a generic narrow $t\bar{t}$ mass resonance.

4.2. Single Top Events. – Besides $t\bar{t}$ -pair production, single top quarks will also be produced via electroweak processes at the LHC. There are three main production channels: the t -channel has the largest cross-section ($\sim 240 \text{ pb}$), followed by tW associated production ($\sim 60 \text{ pb}$) and finally the s -channel ($\sim 10 \text{ pb}$). The single-top production cross-section can give a measurement of the CKM matrix element V_{tb} . The most important backgrounds come from $t\bar{t}$ and W +jets events, which are difficult to reduce. An analysis by ATLAS [8] has shown statistical significance already for $\mathcal{O}(100 \text{ pb}^{-1})$. A study by CMS in [9] shows that the t -channel will be easily observable with 10 fb^{-1} [9]. Furthermore, rescaling the statistical and systematic uncertainties obtained with the 10 fb^{-1} analysis, it is found that single-top production in the t -channel can also be visible at 5σ confidence level even with a luminosity of 1 fb^{-1} .

4.3. Top Charge. – A preliminary study by ATLAS [7] has concluded that it is possible to measure the top charge by pairing the lepton and the b -jet via their invariant mass. The jet-charge computation is made from the charges of the jet tracks weighted by their proximity to the jet axis. A discrimination between charges $+2/3$ and $-4/3$ is possible with 1 fb^{-1} .

4.4. FCNC in Top Decays. – Searches for flavour changing neutral currents in top-quark decays will benefit from the high luminosity and large production cross-section for $t\bar{t}$ pairs. According to a study by CMS [9], with 10 fb^{-1} $t \rightarrow qZ$ and $t \rightarrow q\gamma$ decays will be observable with 5σ significance down to a $\text{BR} \sim 10^{-3}$, comparable to the estimated signals in some Beyond-SM models, such as R -parity violating SUSY. Preliminary results [7] show that even with an integrated luminosity of 1 fb^{-1} ATLAS is sensitive to FCNC decays with $\text{BR}(t \rightarrow qZ) \sim 10^{-3}$ and $\text{BR}(t \rightarrow q\gamma) \sim 10^{-4}$.

5. – Conclusions

The LHC will give high statistics samples of $t\bar{t}$ pairs that will allow detailed studies of the top quark properties. Rediscovery of the top quark is possible already at very small integrated luminosity (10 pb^{-1}). Such a quick confirmation of top-quark pair events will give credibility to possible signals of new physics in the ATLAS and CMS experiments. With more luminosity, ATLAS and CMS will measure precisely many important properties of top quarks and will be sensitive to various sources of new physics, such as $t\bar{t}$ resonances and flavour changing neutral currents. The importance of top quark events at the LHC cannot be emphasised enough.

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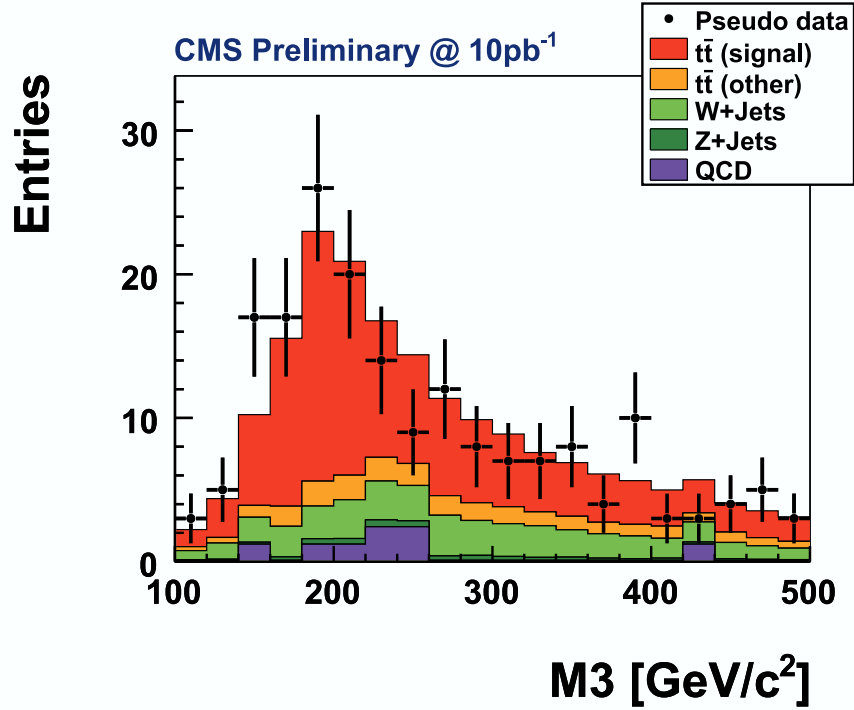


Fig. 1. – CMS Monte Carlo study of the semileptonic muon $t\bar{t}$ channel with the first 10 pb⁻¹ data: invariant mass of the three jets with the highest vectorially-summed E_T .

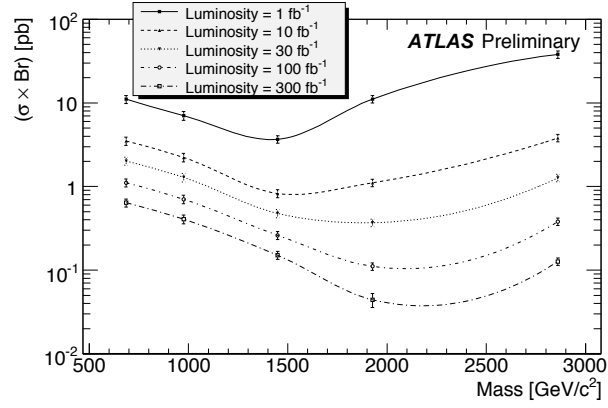


Fig. 2. – Reach for a generic narrow resonance decaying into $t\bar{t}$ pairs in ATLAS.